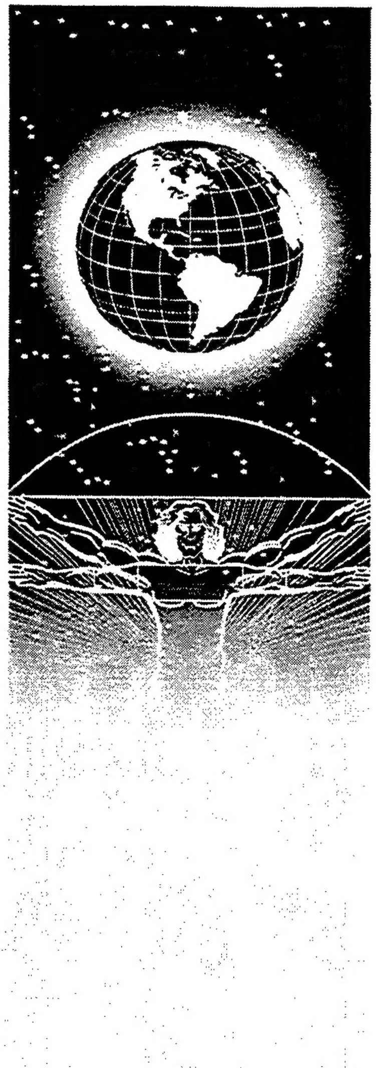
AFRL-HE-WP-TR-2000-0080



UNITED STATES AIR FORCE RESEARCH LABORATORY

Biodynamic Modeling and Simulation of the Ejection Seat/Occupant System

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April 2000

Final Report for the period May 1996 to April 2000

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TECHNICAL REVIEW AND APPROVAL

AFRL-HE-WP-TR-2000-0080

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE DIRECTOR

F. Wesley

F. WESLEY BAUMGARDNER
Acting Chief, Biodynamics and Protection Division
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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 2000	Final Report May 1996 to April 2000

4. TITLE AND SUBTITLE
Biodynamic Modeling and Simulation of the Ejection Seat/Occupant System

5. FUNDING NUMBERS
C: F41624-97-D-6004
PE: 62202F
PR: 7184
TA: 718443
WU: 71844301

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Veridian Engineering
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Human Effectiveness Directorate
Biodynamics and Protection Division
Wright-Patterson AFB OH 45433-7947

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFRL-HE-WP-TR-2000-0080

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words) Ejection seat dynamic characteristics and potential injury to its occupant are essential concerns for evaluating ejection systems. To better assess the interaction between the ejection seat and the occupant, an ejection seat model, EASY5/ACESII, was coupled with an occupant model, ATB. Additionally, the aerodynamics capabilities in both the seat and occupant models were consolidated. The occupant/seat separation algorithms were also designed and implemented. Simulation graphics were reported and various simulation time histories were compared with those from ejection seat sled tests. The integrated model successfully predicts the major features of the ejection seat motion and the crewmember biodynamic responses.

14. SUBJECT TERMS
Ejection Seat, Occupant Modeling, ATB, Aerodynamics, Simulation

15. NUMBER OF PAGES
14

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	10. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UNLIMITED

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ABSTRACT

Ejection seat dynamic characteristics and potential injury to its occupant are essential concerns for evaluating ejection systems. To better assess the interaction between the ejection seat and the occupant, an ejection seat model, EASY5/ACESII, was coupled with an occupant model, the ATB model. Additionally, the aerodynamics capabilities in both the seat and occupant models were consolidated. The occupant/seat separation algorithms were also designed and implemented. Simulation graphics are presented and various simulation time histories are compared against those from ejection seat sled tests. The integrated model successfully predicts the major features of the ejection seat motion and the occupant biodynamic responses in low-speed ejections.

This paper was received for review on 31 March 1999 and was accepted for publication on 21 September 1999.

INTRODUCTION

Assessment of ejection seat performance is complex and life critical. Aspects of ejection seat performance include cockpit, aircraft, and ground clearance, as well as human tolerance to forces imposed by the seat, the parachutes, and windblast. A combination of full system rocket sled and flight test data analysis, and computational modeling, are currently used to quantify seat performance. In testing, much of this work has focused on the measurement of object trajectories and accelerations produced by the seat on the occupant. Many aspects of occupant and occupant/seat interaction dynamics are not captured due to the limitations of test equipment, data recording technology and high-test costs. Computational modeling is a tool used in system development to predict performance and, after testing, to extrapolate performance for extreme flight conditions. Computational models of ejection seats often treat the occupant as a lumped point mass attached to the seat with springs and dampers. More commonly, the occupant is treated as rigidly attached to the seat. Therefore, for most ejection seat models,

dynamic forces introduced to the seat from the occupant are largely overlooked.

In most ejection seat cases, the occupant is the major portion of the seat/occupant combination. Changes in system mass properties and aerodynamics resulting from changes in occupant body position will be sources of error in the present capability to predict ejection seat dynamics. These errors are important relative to ejection seat stability and trajectory shaping. Occupant dynamics play a significant role in seat trajectory and accelerations experienced by the system. Sources of injury potential include those from inadequate limb restraint, poor body positioning, and body segment collision with objects such as the seat structure. Due to the paucity of analytical tools for the design of ejection seat restraints and evaluation of proper body positioning, the performance of a system may not be well understood. Unfortunately, many of these design hazards are found only after injuries and in some cases, fatalities, have resulted.

The goal of this study is to assemble a powerful analytical tool composed of an integrated ejection seat/occupant model using the EASY5/ACESII (Engineering Analysis SYstem/Advanced Concept Ejection Seat) model and the ATB (Articulated Total Body) model for predicting the seat/occupant combination performance. The initial model integration has been completed, and preliminary validation has been performed against the 0-0 (zero airspeed - zero elevation) and 144 KEAS (Knots Equivalent Air Speed) ejection seat tests conducted on the High Speed Test Track at Holloman Air Force Base, New Mexico. The model successfully predicts the major features of the ejection seat motion and the occupant biodynamic responses in the low-speed ejections.

EJECTION SIMULATION MODELS

Mathematical modeling and computer simulations are robust tools for gaining insight into the kinematic and dynamic responses of an escape system. Among many existing models, the EASY5/ACESII ejection seat model and the ATB occupant model are the most prominent models used by the US Air Force and the escape system research community. The EASY5/ACESII ejection seat model provides modeling of ejection seat components, while the ATB model provides modeling of the occupants and their surroundings.

EASY5/ACESII Ejection Seat Model

The EASY5 /ACESII ejection seat model was developed by the US Air Force Research Laboratory (AFRL) running in the EASY5 environment [1, 2, 3, 4]. EASY5 is used for modeling, analyzing, and designing dynamic systems that can be characterized by differential, difference, and algebraic equations. The EASY5/ACESII model is a generalized, multibody, six degrees-of-freedom program that models the major seat components, including the firing control system, propulsion rockets, and parachutes. It is designed for analyzing ejection seat stability and trajectory characteristics and for predicting the system performance throughout the escape envelope. Although overall validation results are judged good for the model, some areas of the model requiring improvement have been identified. Significant limb flail and body motion are evident in many ejection tests, which result in center of gravity (CG) shifts and moment of inertia (MOI) changes for the ejection system. The limb flail and body motion could also affect the overall aerodynamic forces acting on the system. Because a single lumped mass is used to represent the occupant in the EASY5/ACESII model, it is not feasible to simulate the effects of CG and MOI changes during the ejection event. The lack of simulating these changes may induce significant errors in evaluating seat stability and trajectory characteristics. In addition, the inherent limitations of the ejection seat model impede the accurate prediction of occupant injury and evaluation of the effectiveness of the occupant restraint system.

ATB Model

The ATB model is a computer program developed by AFRL for predicting biodynamic responses of humans and manikins during aircraft ejection, aircraft crashes, automobile accidents and other hazardous events [5, 6]. The analytical approach of the ATB model is based on three-dimensional coupled rigid body dynamics using Euler equations of motion with kinematics constraints. An occupant is described as a set of segments that are connected by kinematic joints. External forces are applied to the segments through interaction with other segments, planes, and harness restraint systems. The model has been validated against impact sled tests and fully instrumented vehicle crash tests. It provides rigorous analytical techniques to predict biodynamic responses of an occupant, and to evaluate ejection seat accommodation and effectiveness of restraint systems. However, it is difficult to use the model to simulate the operation process of the escape system such as the event-time sequence control, the rocket catapult firing, and the parachute deployment.

ADVANCED EJECTION SEAT/ OCCUPANT MODEL

Figure 1 demonstrates the seat/occupant modeled using the EASY5/ACESII model and the ATB model, respectively. An integration of both models can make use of the features and capabilities of each model and provide a powerful analytical tool for evaluating escape systems.

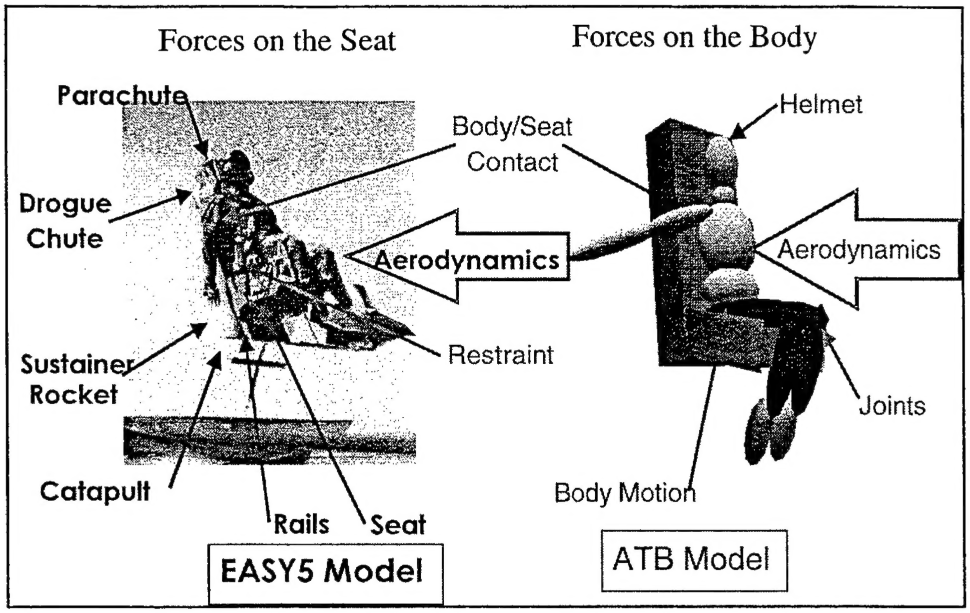

Figure 1. Ejection seat/occupant model.

Model Integration

This integrated ejection seat/ occupant model consists of four major modules: ejection seat module, occupant module, an interface module, and the output module, as shown in Figure 2. The ejection seat module determines the seat motion based on the inertial properties of the seat, forces and torques acting on the seat by the occupant, explosive/non-explosive charges, and the aerodynamic environment. The occupant module calculates the occupant's biodynamic responses based on the ejection seat motion, body segment physical properties, articulating joint characteristics, contact force-deflection properties, aerodynamic environment, and the belt restraint system. A kinematic/dynamic interface module

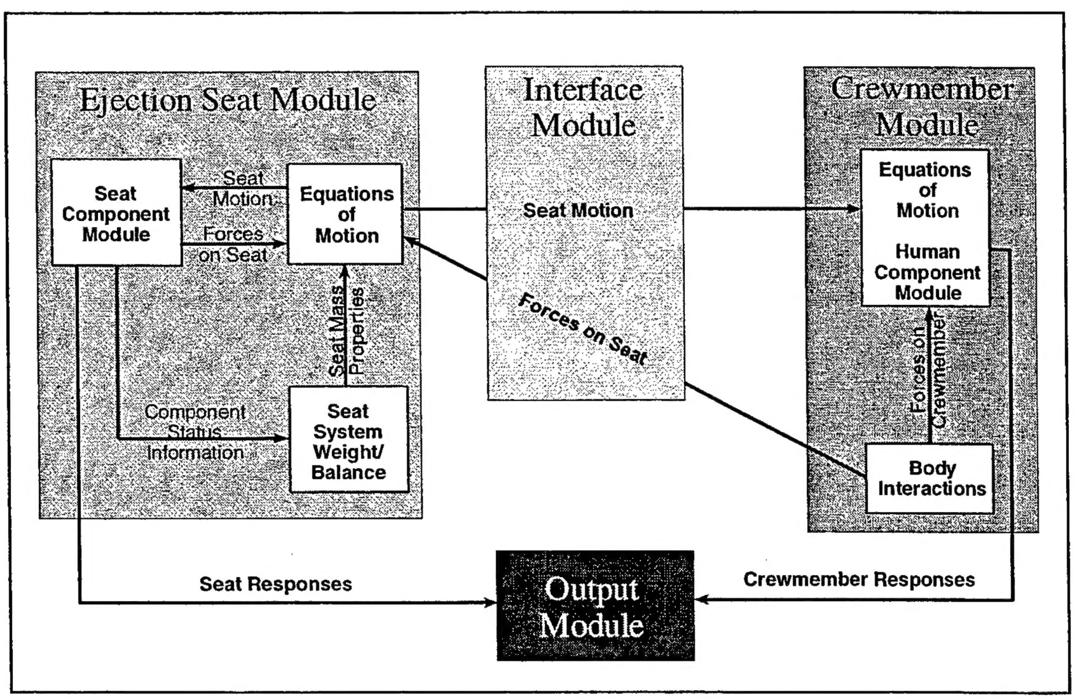

Figure 2. Integrated ejection seat/occupant model.

is designed to connect the ejection seat and the occupant modules, and to coordinate the numerical integration process. The ejection seat motion, calculated by the ejection seat module, is transferred to the occupant module and is used in calculating the occupant's biodynamic response. The forces and torques acting on the ejection seat due to the occupant and restraint system are sent to the ejection seat module, and treated as one of the nonexplosive charges (force mechanisms) to determine the ejection seat motion. The output module generates simulation results such as the ejection event-time sequence; any of the calculated dynamic state variables, and any forces and torques acting on the seat. With respect to the occupant, the output includes the linear and angular positions, velocities, and accelerations of any body segment; the joint angles and torques; contact locations and forces, restraint belt forces, and aerodynamic forces acting on any body segment. These data are provided in time history format. Injury assessment information is also available, including the Dynamic Response Index (DRI), Multi-axial Dynamic Response Criteria (MDRC), lumbar and neck loads, seat/occupant contact loads, and joint forces and torques.

Aerodynamic Capability Consolidation

Aerodynamic effects on ejection seat stability and potential injury to the occupant are a major concern in design and evaluation of an ejection seat. Aerodynamic models from both the ejection seat module and the occupant module are used in the combined ejection seat/occupant model. In the ejection seat module, the aerodynamic characteristics for the ejection seat/occupant combination are determined by accessing a large aerodynamic coefficient database that is primarily gathered on half scale models in AEDC's (Arnold Engineering Development Center) 16 foot transonic tunnel [7, 8]. Figure 3 shows a full-scale ACES II installation in the AEDC wind tunnel. The coefficients vary with the Mach number, the seat orientation relative to the wind stream, and the occupant size. Effects of propulsive rockets and aircraft proximity are also taken into account as these will alter the pressure fields around the seat/occupant, and change the aerodynamic coefficients. The ejection seat module uses the seat's orientation, position and speed to find the force and torque coefficients in the wind tunnel-generated data matrix. The module starts to calculate aerodynamic forces and torques on the seat/occupant combination as it passes through a windstream plane fixed to the cockpit.

In the occupant module, the aerodynamic forces are applied to any segments that penetrate a windstream plane, as shown in Figure 4. Once a segment's ellipsoid penetrates the wind plane, the projected area normal to the wind stream is calculated, and the forces are computed by multiplying the dynamic pressure by the wetted area and the drag coefficient. There are two types of wind pressure functions available in the occupant module. The first is a time-dependent wind pressure function that gives three components of the wind pressure. The second type computes the wind pressure vector as a function of the relative velocity of a segment. Additionally, there is an option to account for the blocked wind where the body segments substantially overlap.

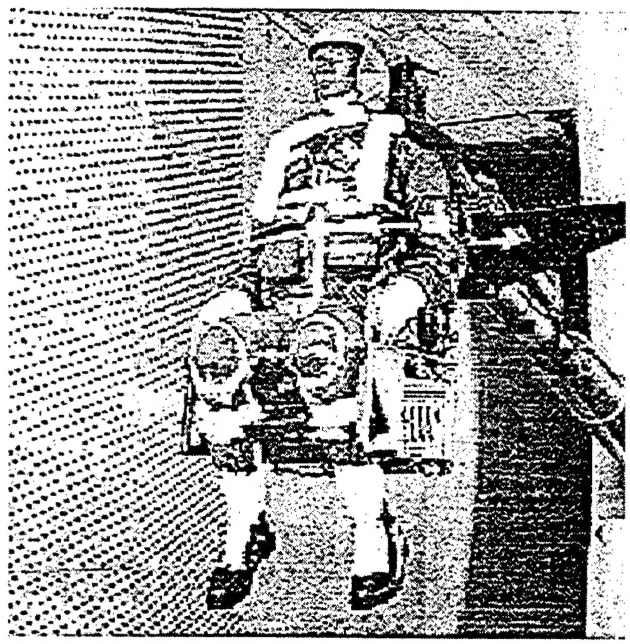

Figure 3. ACES II installation in AEDC wind tunnel.

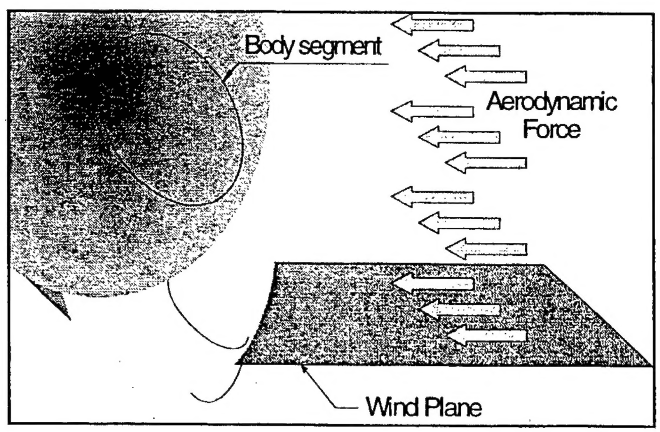

Figure 4. The ATB aerodynamic model.

In the ejection seat module, the windblast acts on the seat/occupant combination. In the occupant module, aerodynamic forces and torques apply only to the occupant's body segments. Therefore, the aerodynamic forces and torques acting on the occupant are duplicated in the combined ejection seat/occupant model. To integrate the aerodynamic capabilities of both models and to better use all the features available, the aerodynamic model in the ejection seat module is used to determine the aerodynamic effects on the seat. The aerodynamic model in the occupant module, on the other hand, is employed to evaluate the aerodynamic forces and torques on the occupant.

To this end, aerodynamic forces and torques on the seat are separated from those on the occupant. Wind tunnel data from the ejection seat module are used to obtain the total aerodynamic force and torque on the seat/occupant combination. The measured total aerodynamic force in the wind tunnel test $\mathbf{F}_{seat/man}$ can be expressed as two components

$$\mathbf{F}_{seat\,/\,man} = \mathbf{F}_{seat} + \mathbf{F}_{man} \tag{1}$$

Where $\mathbf{F}_{seat}$ is the force component on the ejection seat, and $\mathbf{F}_{man}$ is the force component on the occupant. At the same time, the aerodynamic force $\mathbf{F}_{man}$ on the occupant is calculated using forces on each individual body segment from the occupant module.

$$\mathbf{F}_{man} = \sum_{i=1}^{n} \mathbf{F}_{ith}^{seg} \tag{2}$$

Where $\mathbf{F}_{ith}^{seg}$ is the aerodynamic force acting on the i^{th} body segment ($i = 1,n$). These forces and associated torques are applied to the body segments by the occupant module. The occupant aerodynamic force and torque are then transferred to the ejection seat module and subtracted from the total force and torque to obtain the components applied directly on the seat.

$$\mathbf{F}_{seat} = \mathbf{F}_{seat\,/\,man} - \sum_{i=1}^{n} \mathbf{F}_{ith}^{seg} \tag{3}$$

This force and associated torque are applied to the seat by the ejection seat module. Once the seat and occupant start to separate, the force and torque calculated from the occupant module are applied only to the occupant and no longer passed to the ejection seat. To implement these algorithms, the related codes were programmed and/or modified to facilitate the aerodynamic model integration.

Seat/occupant Separation

It is important to understand the dynamic interaction between the seat and occupant to fully evaluate the seat performance during the very short period of their separation. The occupant/seat separation process starts when the harness release mechanism releases the occupant from the seat as the lap belt and inertial reel pins are withdrawn during the automatic recovery sequence. Release of the seat pan latch allows the seat pan to rotate and allows the survival kit to be withdrawn from the seat bucket. The recovery parachute then lifts the occupant from the seat. The harness release and occupant/seat separation processes were investigated and the related algorithms were designed for the integrated ejection seat/occupant model. When the release signal of the harness restraint is generated in the ejection seat module's control sequencer, it is sent to the occupant module. The harness/belt in the occupant module is cut off and releases the occupant from the seat during the automatic recovery sequence. In the meantime, the recovery parachute force and torque from the ejection seat module are transferred to the occupant module and applied to the occupant's upper chest. The combined forces from gravity, recovery parachute, and aerodynamics separate the ejection seat and occupant.

VALIDATION AND DISCUSSION

Ejection Seat Tests

Validation of the integrated model ensures that the simulation results are within a satisfactory accuracy range compared to ejection seat tests, and relative to prediction of major features of both the ejection seat motion and the occupant's biodynamic responses. Simulations of a wide range of previously conducted ejection tests are planned. The first tests to be simulated were a zero airspeed-zero elevation test and a 144 KEAS ejection seat test [9, 10]. Both tests used a standard F-16 configuration seat with the ARS (Advanced Recovery Sequencer). The zero-zero test used a 95th percentile GARD (Grumman-Alderson Research Dummy), and the 144 KEAS test utilized a large ADAM (Advanced Dynamic Anthropomorphic Manikin). Both were dressed in standard personal flight equipment.

Simulation Input Description

In input files, fifteen body segments connected by fourteen kinematic joints were used to represent the dummy. Based on the mass and stature of the dummies, the inertial and geometric data for these body segments were generated using the GEBOD (GEnerator of BOdy Data) program [11]. The cockpit layout, including the

floor, seat, and rudder pedals, was based on the F-16 ACES II general configuration. The ejection seat back reclined 30^0 from vertical and the seat pan inclined 30^0 from horizontal as illustrated in Figure 5. The angle between the seat back and guide rails was 4.5^0. In order to describe the compliance properties between the occupant's segments and the seat panels, force-deflection characteristics were modeled and included in the simulation. A conventional double shoulder strap and lap belt harness were used for restraining the occupant. The contact force-deflection and belt stress-strain functions were taken from other validated occupant simulations [12,13].

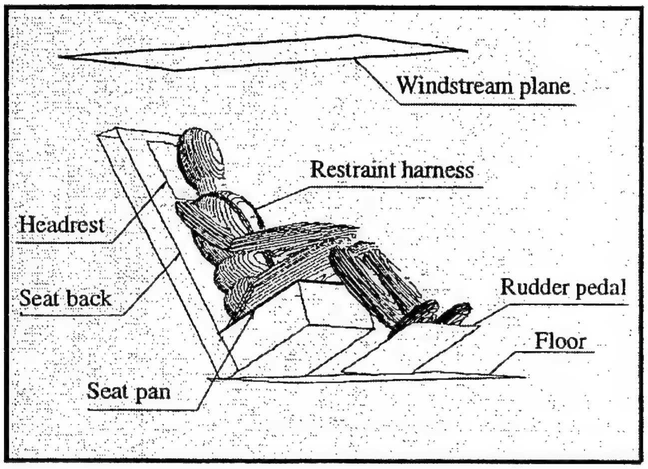

Figure 5. The ACESII-ATB simulation setup.

0-0 Test Simulation Results

Figure 6 shows a graphic sequence portraying the occupant and the ejection seat in the 0-0 ejection seat simulation. At time zero, the rocket-catapult fires and the seat starts to move up along the rail. As the seat approaches the top of the guide rails after about 180 ms, the STAPAC (STAble PACkge) system ignites to provide a counter force to prevent extreme fore/aft pitching. The recovery parachute mortar initiates at about 200 ms after rocket catapult ignition. The harness release thruster is actuated at about 450 ms, and the deploying parachute separates the occupant from the seat. The parachute inflates to a reefed configuration until the reefing line cutters actuate to permit full inflation. Simulation VIEW graphics present physically reasonable results.

Transducer results were also used to validate the ACESII-ATB model. The seat actual accelerations were measured using triaxial accelerometers installed in the seat pan. Figures 7 and 8 illustrate the comparison of the tested and simulated seat accelerations. The seat accelerations in the X and Z directions match very well with the test data up to STAPAC ignition and parachute deployment. However, there were some differences in the acceleration peak values after the parachute deployed. The simulated peak acceleration in the X direction was greater than that tested. On the other hand, the simulated peak acceleration in the Z direction was less than that tested. These differences were likely due to the difficulty in accurately modeling the seat ballistic components and the unstable characteristics of the ejection seat system.

144 KEAS Test Simulation Results

Figure 9 shows the graphic time sequence from the combined model simulating the 144 KEAS ejection seat test. The zero time frame shows the occupant position just as the ejection is initiated. The graphic sequence portraying the occupant and the ejection seat compares extremely well with those of the high-speed film covering the test from seat initiation through the catapult and rocket phase, up until seat/occupant separation. However, some differences have been observed. An approximately 100 ms time-shift between the test film and the simulation view graphics occurs after the seat/occupant separation. Figures 10 and 11 show comparisons of the tested and simulated seat accelerations. The accelerations in the X and Z directions match very well with those of the tested results. The predicted head accelerations in the Z acceleration as shown in Figure 12 also agree very well with that of the test in terms of pulse shape.

CONCLUSIONS

The EASY5/ACESII ejection seat model was successfully integrated with the ATB occupant model. Aerodynamic capabilities were consolidated using features from both the ejection seat and occupant modules. Additionally, the harness release and occupant/seat separation processes were investigated and the related algorithms were designed and implemented. Preliminary validation was performed by correlating selected biodynamic responses in the simulations with those in the ejection sled tests. The integrated ejection seat/occupant model successfully predicts the major features of the ejection seat motion and the occupant biodynamic responses in low-speed ejections.

Through the development and integration of the complete ejection seat/occupant model, a unique and innovative tool has been provided systems modeling and simulation of escape systems. The integrated model will help in developing crew escape systems and improving crew safety and survivability.

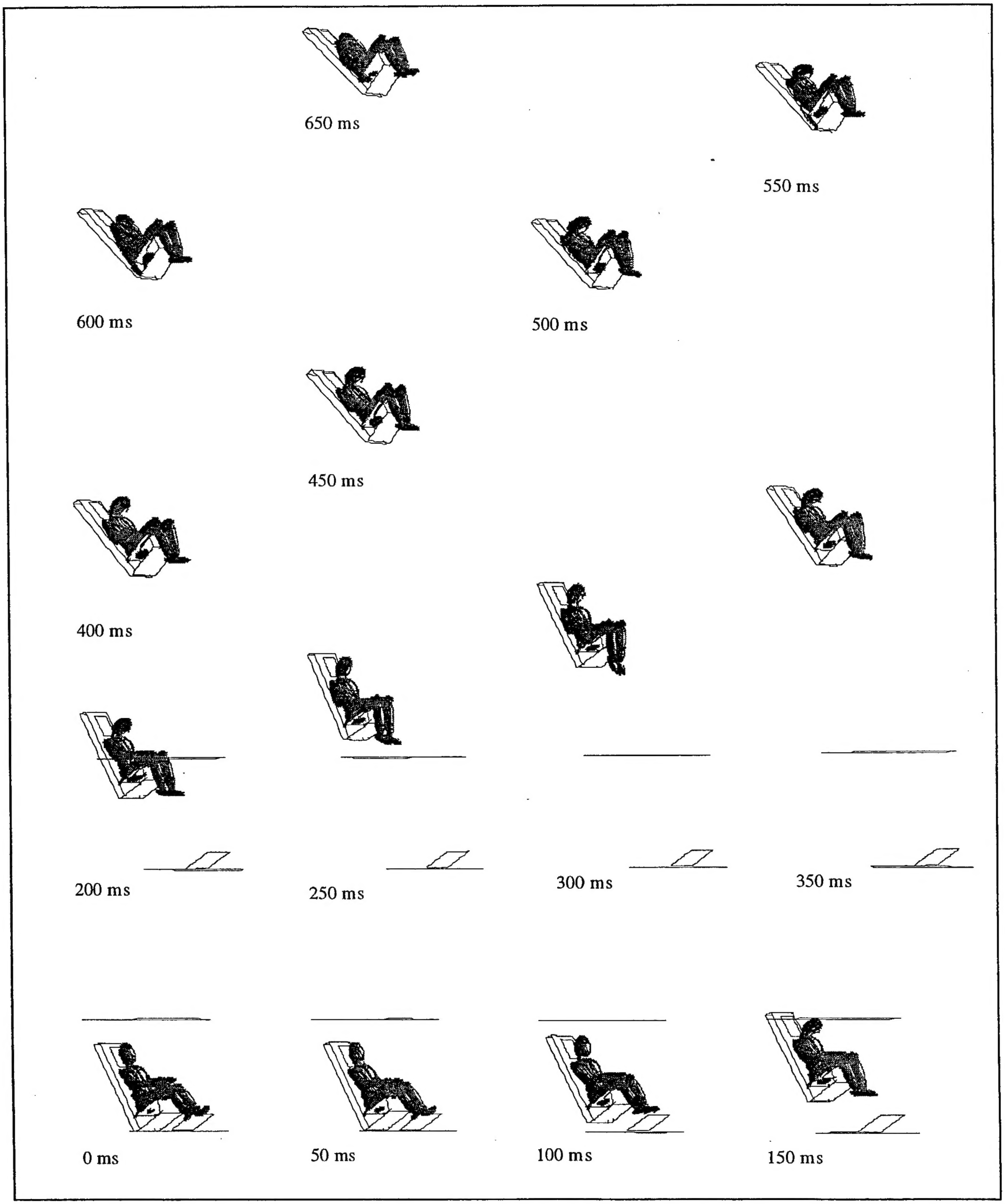

Figure 6. Graphic sequence of the 0-0 ejection seat/occupant simulation.

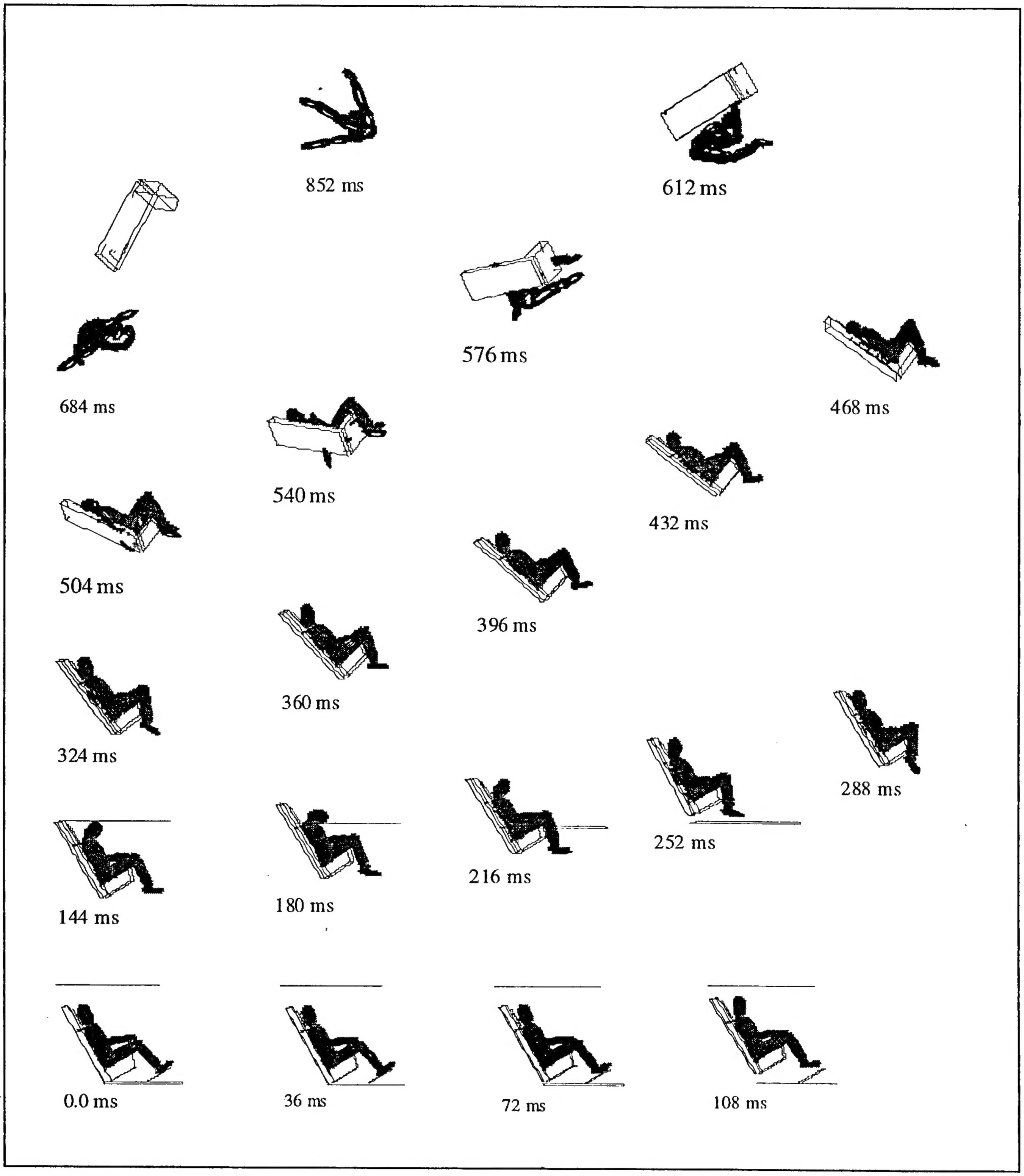

Figure 9. Graphic sequence of the 144 KEAS ejection seat/occupant simulation.

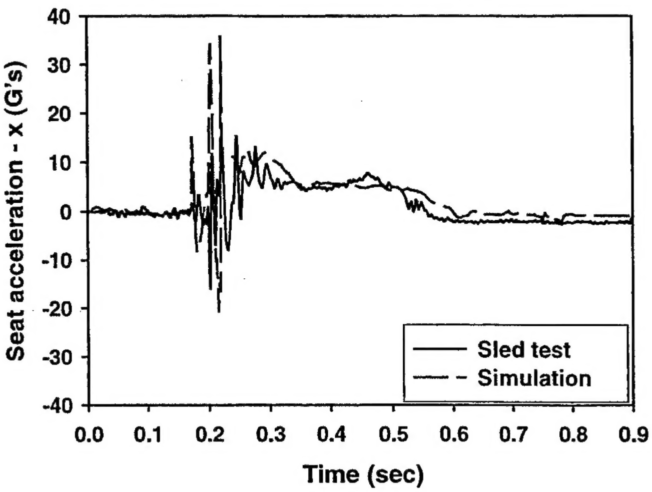

Figure 7. Comparison of seat accelerations-Z (0-0 case).

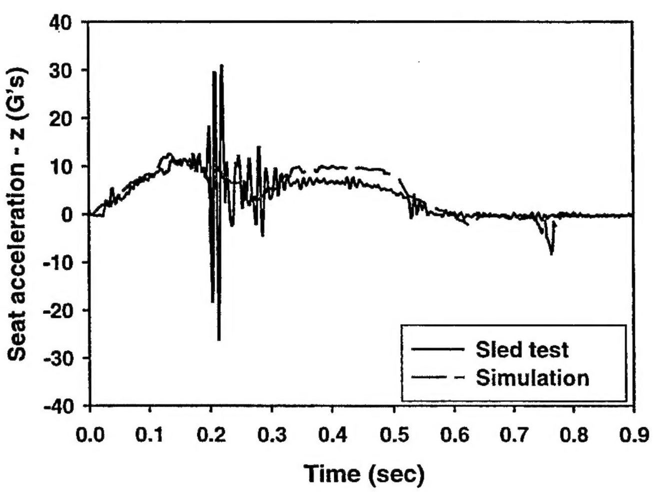

Figure 8. Comparison of seat accelerations-X (0-0 case).

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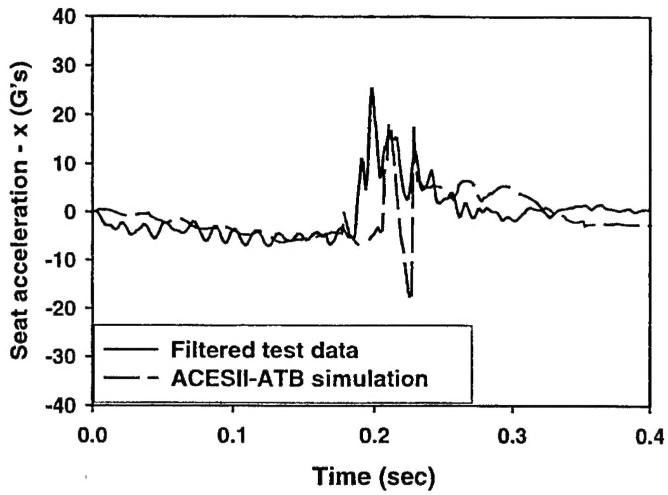

Figure 10. Comparison of seat accelerations-X (144 KEAS case).

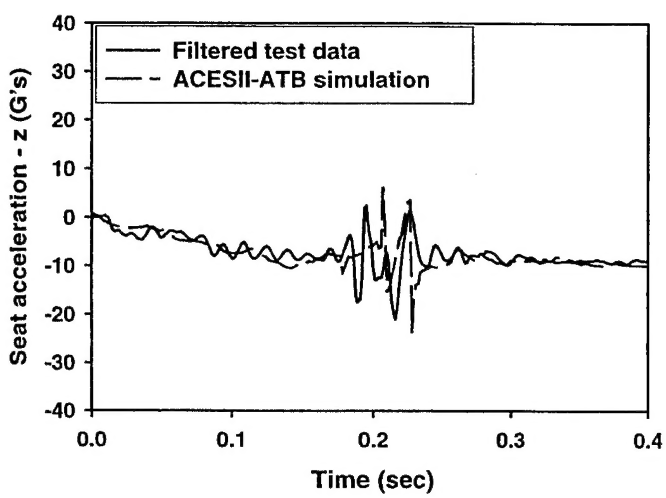

Figure 11. Comparison of seat accelerations-Z (144 KEAS case).

Dr. Louise Obergefell is a mechanical engineer with AFRL at WPAFB. She received a B.S. and M.S. in Mechanical Engineering from the University of Dayton and Ph.D. from the Univ. of Cincinnati. Her work with the ATB model has included developing a methodology for simulating occupant motion during ejection and automobile rollover. She has used the model to conduct numerous studies investigating occupant dynamics for the Air Force and the Department of Transportation.

Ms. Annette Rizer is a systems engineer at Veridian, supporting the modeling efforts at AFRL. She received a B.S.E. in Biomedical Engineering from Wright State University. Her experience with the ATB model includes development of a method to simulate vehicle motion during rollover, development of test dummy databases, and various modifications to improve the program.

Mr. Lawrence Rogers is an Aeronautical Engineer in the Flight Systems Branch of the Engineering Directorate at WPAFB. He received his M.S. in Aerospace Engineering from the University of Dayton and a B.S.A.A.E from the Ohio State University. His experience includes authoring escape system models and application of existing models to support the development of ejection seats, canopies, manual bailout, and paratrooper airdrop capabilities for USAF weapons platforms.

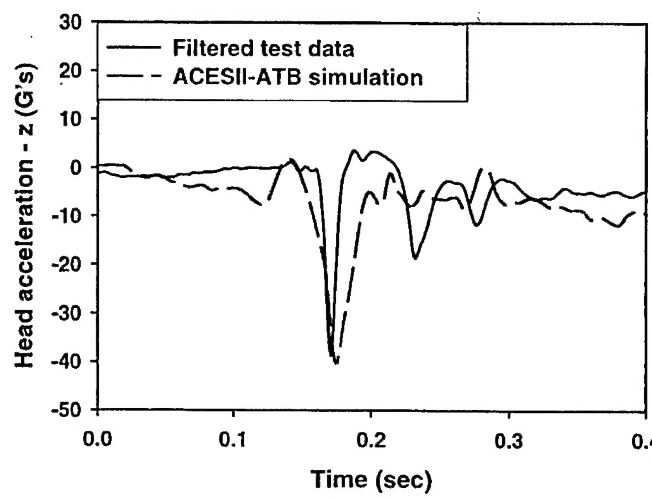

Figure 12. Comparison of pilot head accelerations-Z (144 KEAS case).